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Title: Spot-size Enlargement due to Pulsed-Power Fault Modes:II. Injector Faults

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Spot-size Enlargement due to Pulsed-Power Fault Modes: II. Injector Faults

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Scorpius is reasonably robust to pulsed-power faults in the injector.

Pulsed-power faults can enlarge the radiographic source spot. We have investigated this with numerical experiments.

- LIA faults result in beam energy reduced from expected. There are two distinct types of acceleration faults.
  - Short circuited gaps due to insulator flashover or vacuum arc result in approximately zero voltage across gap if the arc resistance is << 10 Ohms.
  - Loss of SSPP units can result in deceleration across gap due to beam loading.
  - Both types cause spot enlargement due to reduced focal length of final-focus magnet.
  - Both types can cause mismatched beam transport with emittance growth that further enlarges the spot.
- **Injector faults result in reduced current in addition to reduced energy, and also modified beam parameters entering the LIA.**
  - **The spot is enlarged due to reduced focal length of final-focus magnet.**
  - **Mismatched beam transport with emittance growth also enlarges the spot.**
- **Codes well suited for investigating these effects are the XTR envelope code, and the LSP PIC code, using the slice algorithm to avoid numerical instability and reduce computation time.**
  - **Initial conditions required by these codes were derived from LLNL TRAK simulations of the redesign with 1:1 push-pull ratio**

Initial conditions at the exit of the 1:1 redesign diode were derived from TRAK simulations.

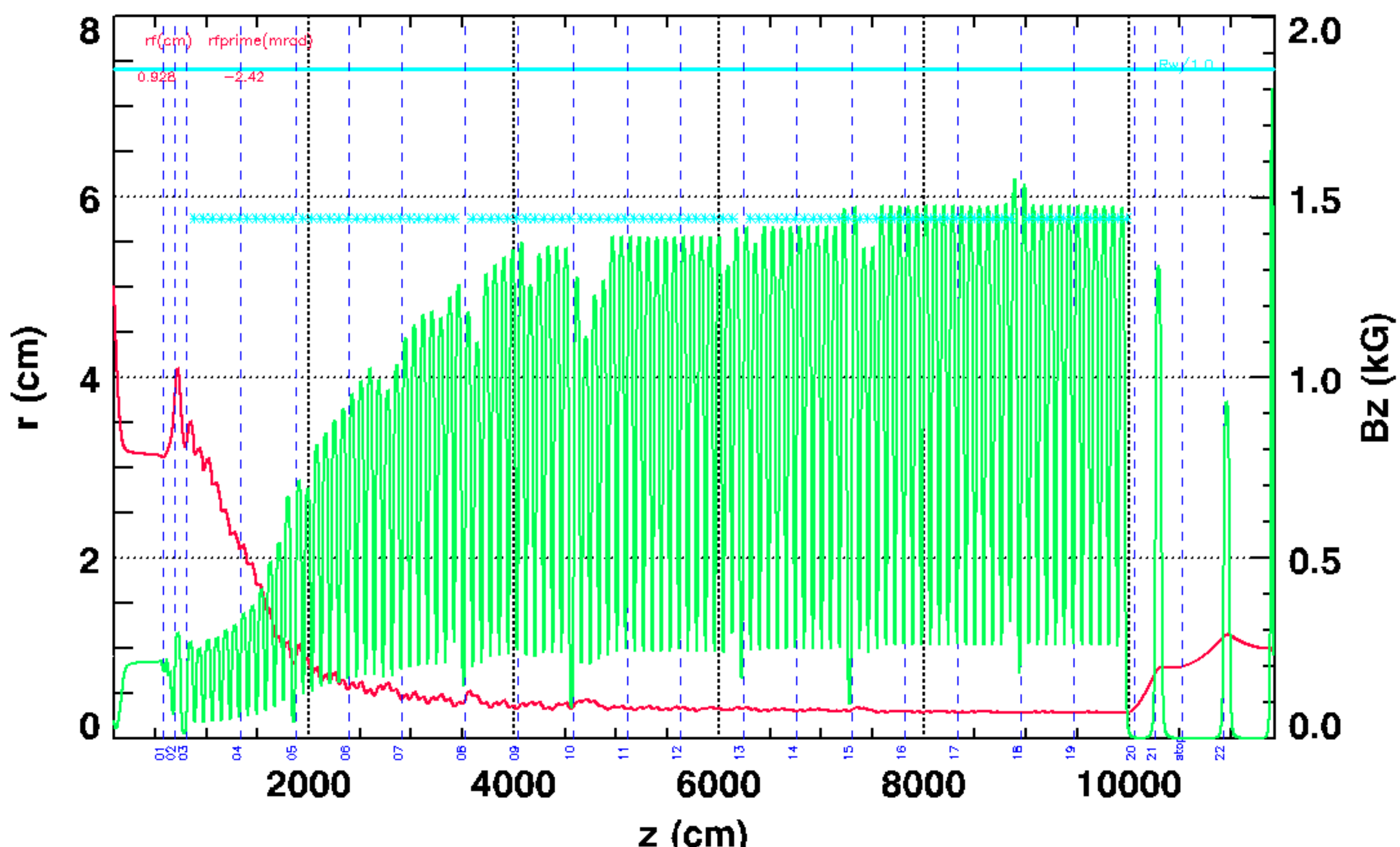
- TRAK lists $\langle r^2\rangle^{1/2}$, $\langle r'^2\rangle^{1/2}$, and 4-rms (Lapostolle) emittance at z = 1 m
- The required initial conditions R_{env} and R'_{env} were derived from these.

Case	Cathode dV_K kV	Anode dV_A kV	Energy KE MeV	Current I_b kA	Normalized Emittance en (4-rms) cm-radian	Envelope Radius R cm	Envelope Convergence R' mr
(CE)	0	0	2.000	1.4452	0.0204	5.011	-35.235
(WS)	0	0	2.000	1.4710	0.0205	5.102	-34.794
1	-25	0	1.975	1.4366	0.0204	4.979	-36.940
2	0	-25	1.975	1.4545	0.0209	5.045	-36.732
3	-25	-25	1.950	1.4203	0.0209	4.917	-38.953
4	-50	0	1.950	1.4025	0.0204	4.852	-39.138
5	0	-50	1.950	1.4382	0.0211	4.984	-38.760
6	-50	-50	1.900	1.3701	0.0210	4.717	-43.371
7	-350	0	1.650	1.0093	0.0267	2.936	-68.584
8	0	-350	1.650	1.2448	0.0311	3.864	-70.459

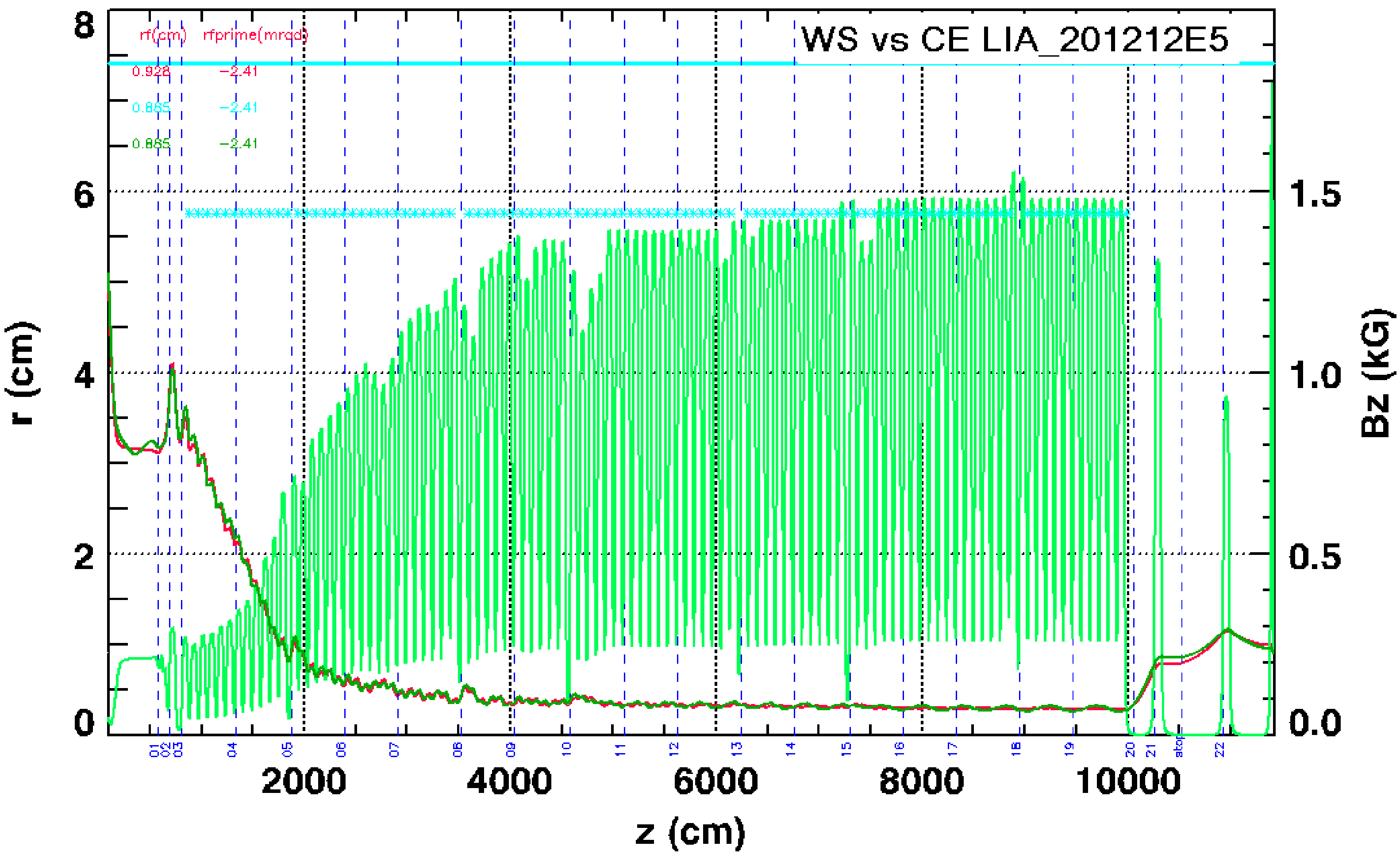
Initial conditions for the CE nominal tune for the anode, LIA, and DST were obtained by reducing the bucking coil by 6% to better null the Larmor emittance (P_θ/mc) at the cathode.

For this investigation we used the nominal tune that is also being used to assess beam stability.

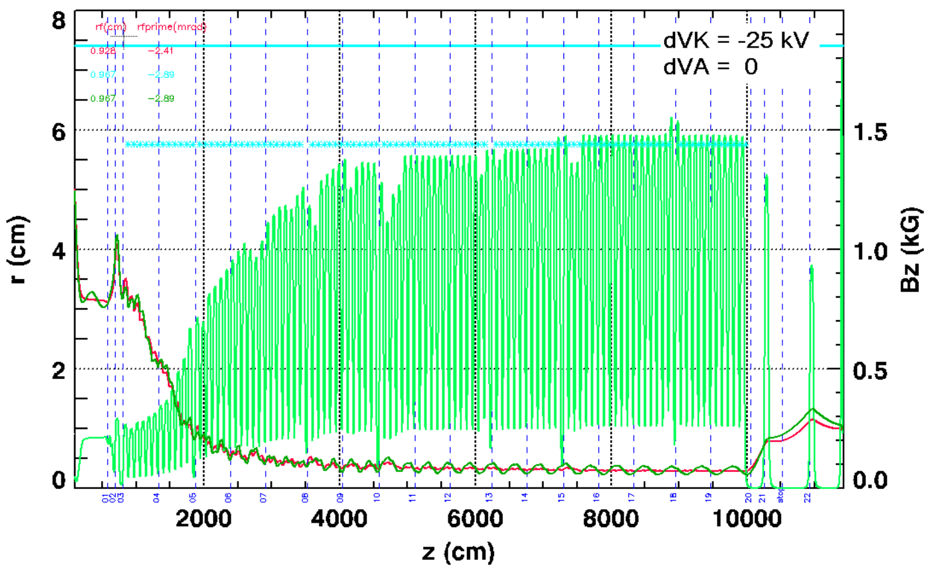
- This tune was designed to match a beam with CE initial conditions.
- An envelope-stable, matched beam is transported and accelerated through the LIA.
- Maximum field less than 1.5 kG suppresses BBU growth to less than on DARHT-I.
- The DST is tuned for optimally-sized waist (R ≈ 1cm) entering the final focus solenoid.

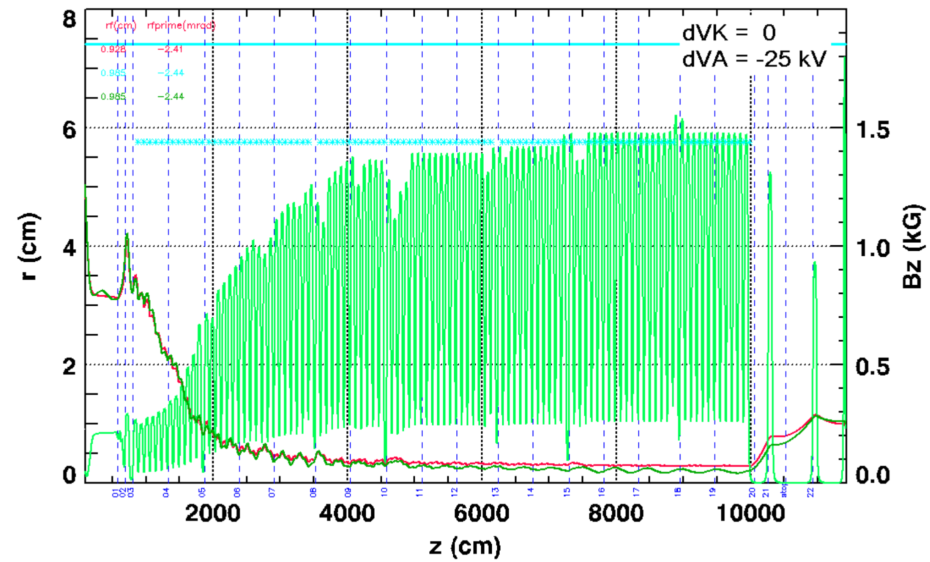


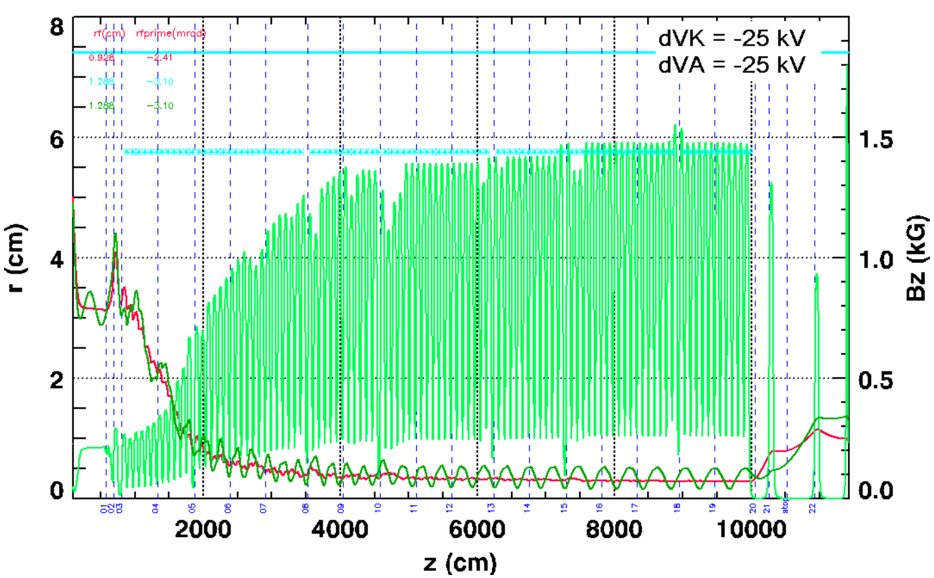
Recent diode simulations with TRAK produced slightly different initial conditions than those used for tune design.



Injector SSPP stack failures change the beam initial conditions enough to cause a mismatch of the beam to the solenoidal focusing tune.



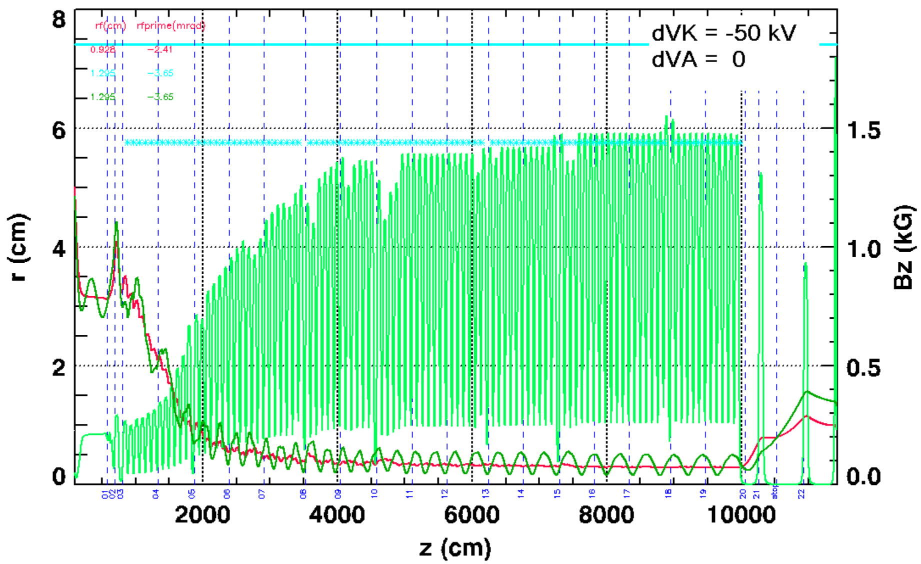


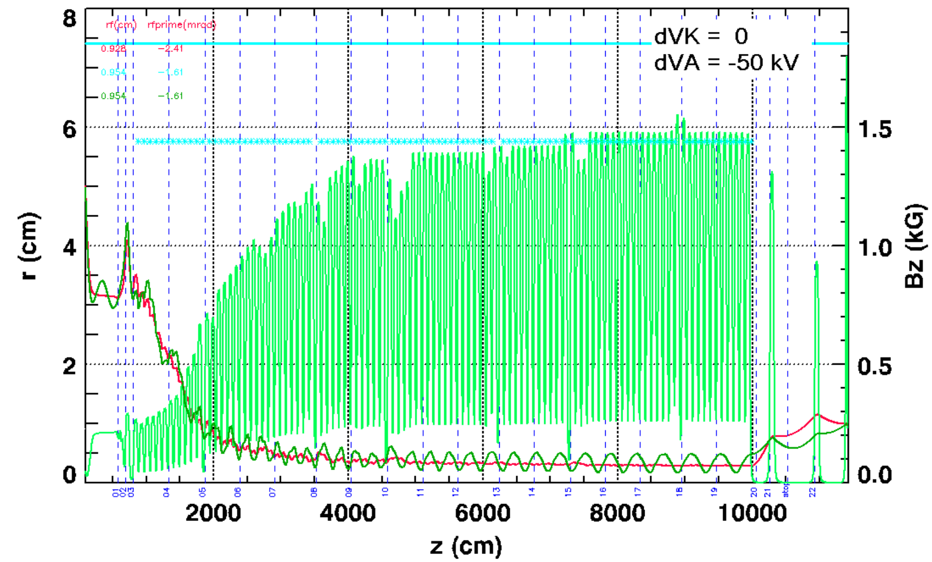


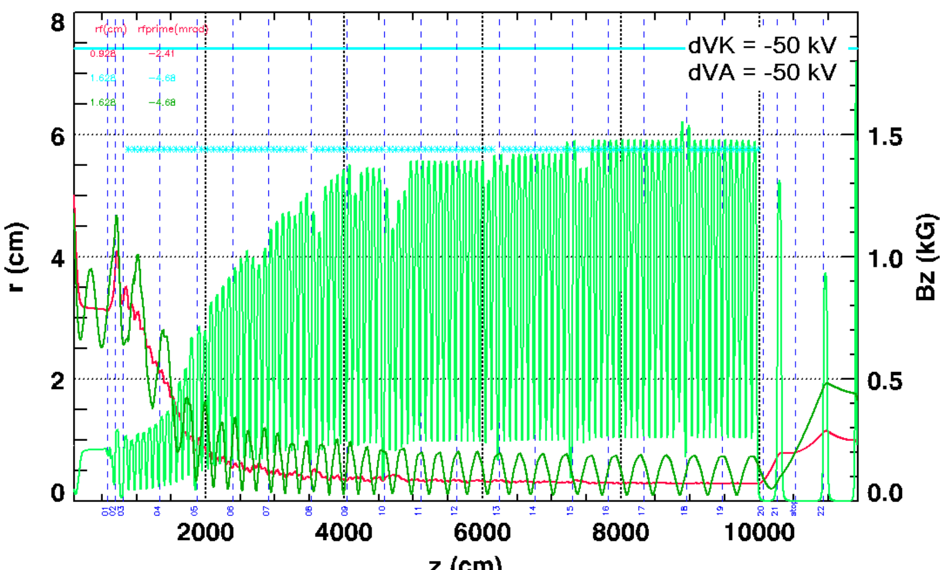
Substantial envelope mismatch due to failures of pulse power can result in emittance growth and source-spot enlargement.

This needs to be investigated using LSP-S.

Breakdown of injector-cell gaps can be disastrous.







Very large envelope oscillations can lead to significant emittance growth through parametric halo generation.

This needs to be investigated using LSP-S.

Emittance growth and final-focus solenoid entrance conditions were evaluated using the LSP slice algorithm.

- Launch and evaluate LSP-Slice (LSP-S) at upright phase-ellipse locations.
  - ref: SWS 12/20 presentation

- LSP-S launched at envelope maximum between injector and LIA
  - z_0 = 722 cm (upright phase-ellipse)

- LSP-S launch parameters were obtained using XTR transport from diode
  - z = 100 cm to 722 cm (through the anode)

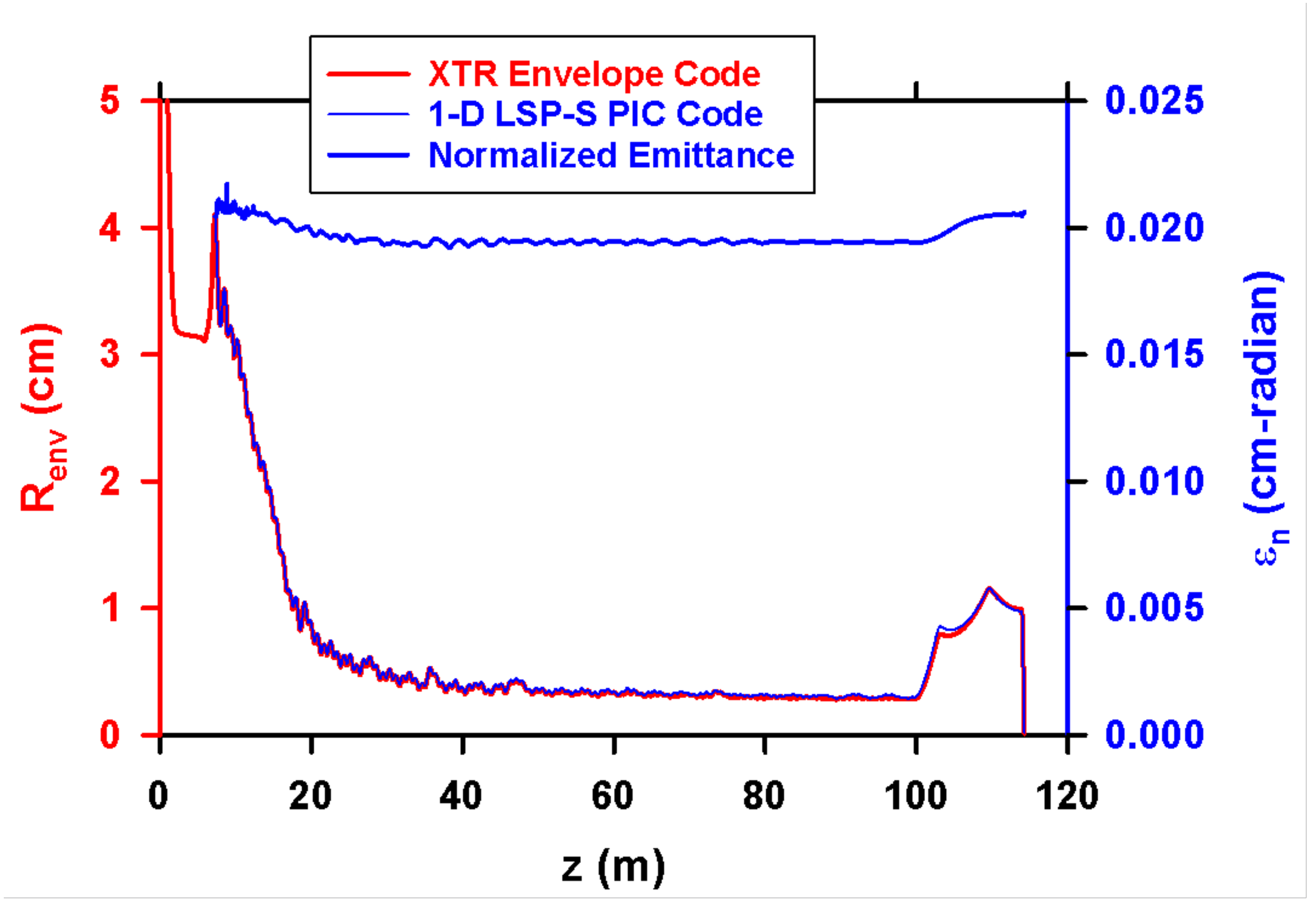
- LSP-S parameters were obtained at entrance to final focus solenoid
  - z_f = 11370 cm (beam waist for nominal tune, upright phase-ellipse))

Initial conditions for launching LSP-S were obtained from XTR simulations from the diode to the launch point.

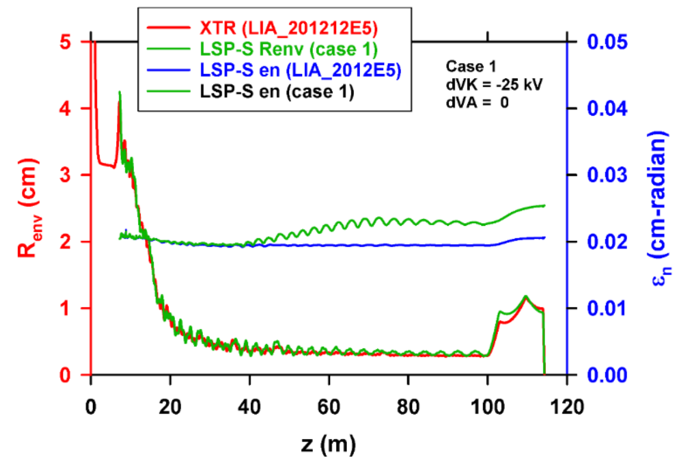
- Rigid-rotor LSP-S launch model is most accurate for upright phase-ellipse.
- The phase-ellipse is upright (R' = 0) at the z=722 cm launch point for the nominal tune, and within a few cm for the first several fault cases.

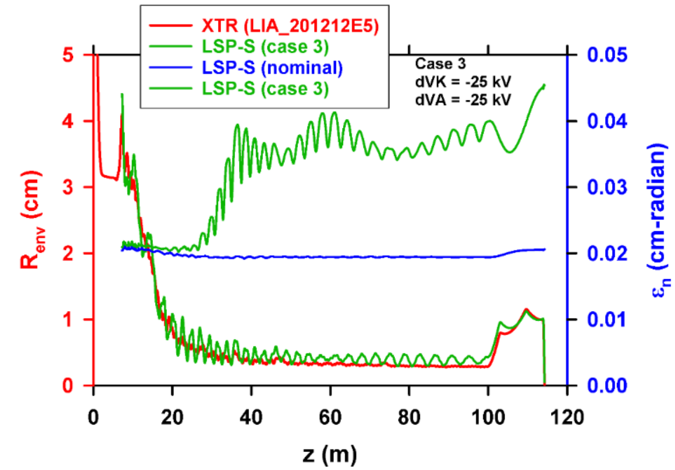
Case	Cathode dV_K kV	Anode dV_A kV	Energy KE MeV	Current I_b kA	Normalized Emittance en (4-rms) cm-radian	Envelope Radius R cm	Envelope Convergence R' mr
(CE)	0	0	2.000	1.4452	0.0204	4.0986	0.00
(WS)	0	0	2.000	1.4710	0.0205	4.0472	0.20
1	-25	0	1.975	1.4366	0.0204	4.2451	-1.20
2	0	-25	1.975	1.4545	0.0209	4.2199	-1.20
3	-25	-25	1.950	1.4203	0.0209	4.4086	-3.60
4	-50	0	1.950	1.4025	0.0204	4.4227	-4.20
5	0	-50	1.950	1.4382	0.0211	4.3830	-3.00
6	-50	-50	1.900	1.3701	0.0210	4.6488	-10.40
7	-350	0	1.650	1.0093	0.0267	2.4179	50.20
8	0	-350	1.650	1.2448	0.0311	1.8071	8.40

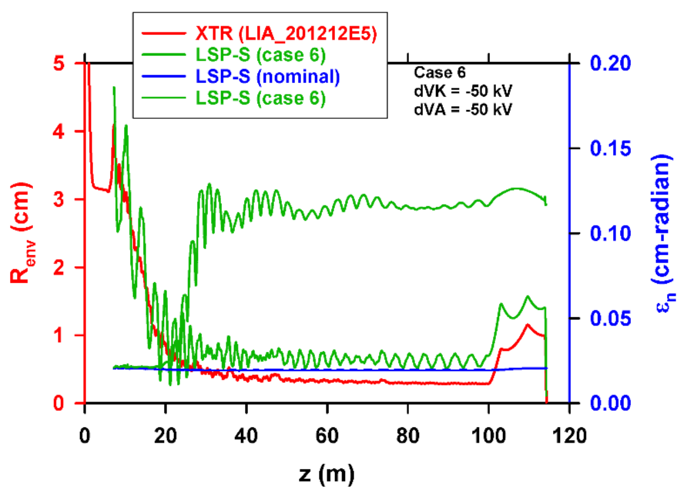
Results of XTR envelope and LSP-S PIC simulations agree for my nominal LIA tune with optimized DST (LIA_201212E5).

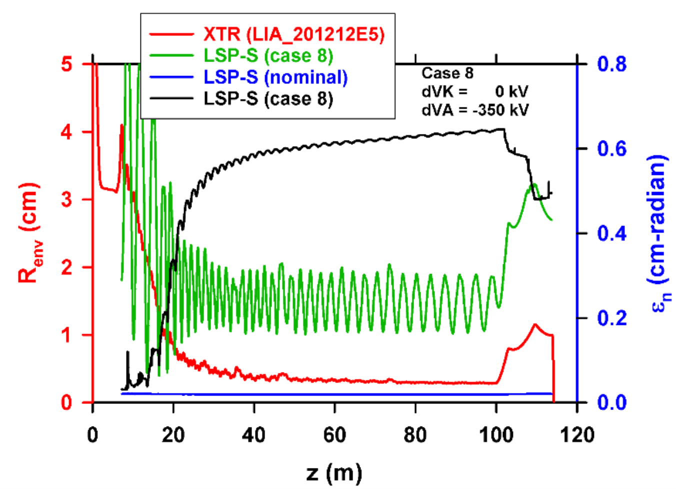


Pulse-power faults in the injector can cause substantial emittance growth due to mismatched beam injection.









- **Matched beam radius is proportional to $\varepsilon^{1/2}$**
- **Emittance growth saturates due to nonlinear halo dynamics [TPS,2017]**

The implication of fault modes for radiography was evaluated by calculating spot size from the beam parameters at the FF entrance.

- **Spot size from XTR simulations does not include emittance growth, aberrations, or beam motion.**
- **Spot size from LSP Slice simulations cannot resolve current distribution details at focal spot with practical zoning and run time.**
- **Neither include beam-target physics.**
- **Spot-size estimates were based on the variance formalism of J. D. Lawson, A. C. Paul, Y. J. Chen and others using rms beam radius.**
- **d_{LANL} (50% MTF) calculated from rms for a Gaussian distribution, such as observed in DARHT-II experiments. ($d_{LANL} = 2.66\ r_{rms}$)**

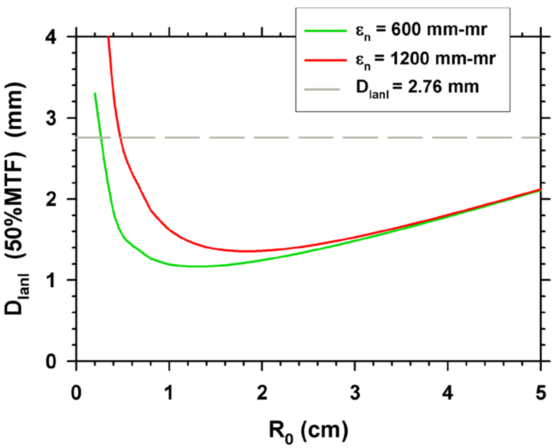
In the absence of beam target effect, spot size can be optimized if there is sufficient knowledge of beam parameters.

$$r_{spot}^2 = \underbrace{\left(\frac{\varepsilon_n f}{\beta\gamma R_0}\right)^2}_{\text{Fundamental Minimum}} + \underbrace{\sum R_{aberrations}^2}_{\text{Focusing}} + \underbrace{\sum R_{motion\ blur}^2}_{\text{Instabilities}}$$

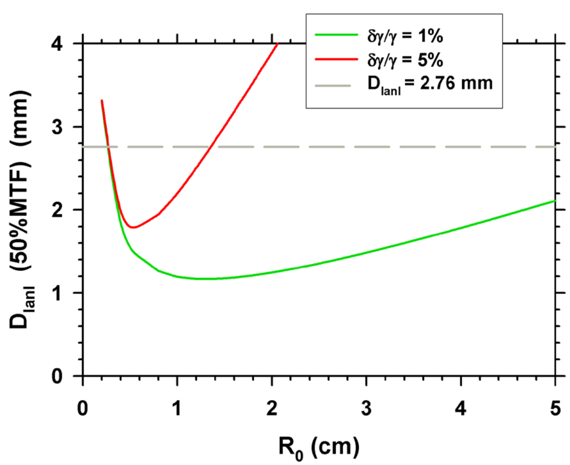
Beam parameters that are under some degree of control (emittance, energy spread, and beam motion) all contribute to an enlarged spot size.

$$r_{spot}^2 = \left(\frac{\varepsilon_n f}{\beta\gamma R_0}\right)^2 + \left(\frac{2\delta\gamma}{\gamma} R_0\right)^2 + \left(C_S R_0^3\right)^2 + \left(r_\varepsilon \Delta R_0 / R_0\right)^2$$

Influence of emittance on optimum DST tune



Influence of energy spread on optimum DST tune

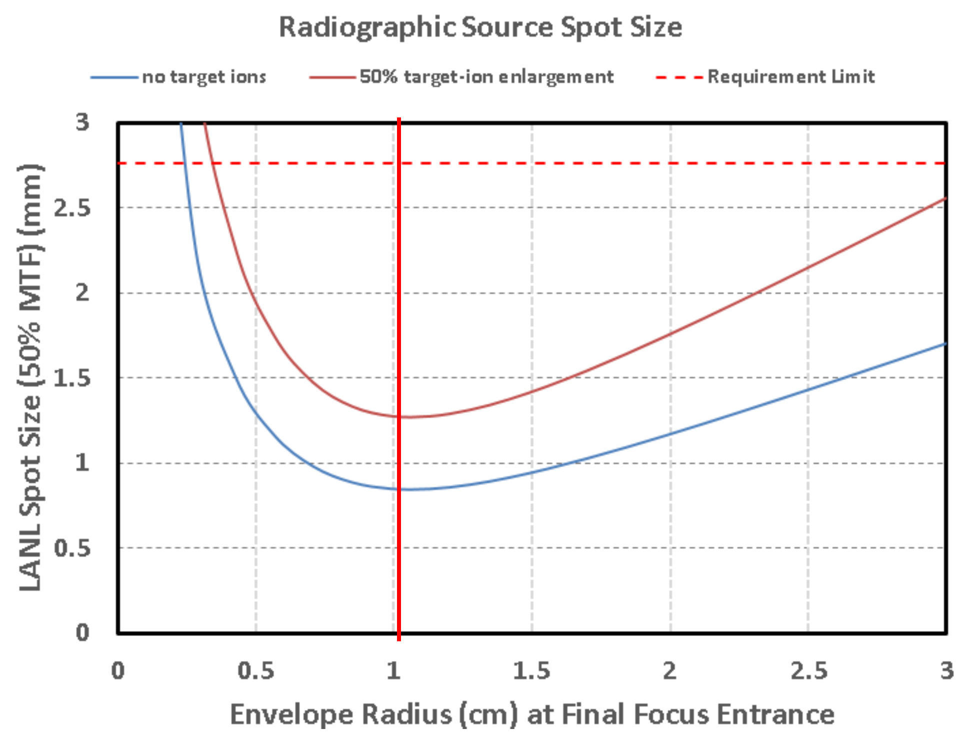


- **Beam Motion is negligible for dR/R< 10%**

Optimizing the beam size at the final focus solenoid minimizes the spot size with requirement-limited beam parameters.

Requirements:

- Emittance
  - $\varepsilon_n <$ 600 mm-mr
  - Normalized 4-rms (Lapostolle)
- Energy spread
  - $\delta\gamma/\gamma < 1.5\%$
  - Time integrated
- Beam Motion
  - $dR_0/R_0 < 10\%$
  - (DARHT requirement)
- RMS calculation, conversion of results to:
  - R_0 :: envelope = $2^{1/2}$ x rms
  - dLANL :: Gaussian = 2.66 x rms



Optimum envelope at FF entrance: $R_0 \approx 1$ cm

(Time integrated enlargement due target-ion defocusing has been observed to be about twice the minimum in TRSS measurements without a barrier)

The loss of one or two injector cells does not fatally enlarge the radiographic source spot.

- Spot sizes were calculated assuming a Gaussian profile, in accordance with experimental observations.
- At requirement limits ($d\gamma/\gamma = 1.5\%$, $\varepsilon_n = 600$ mm-mr) the size would be $d_{LANL} = 0.85$ mm in absence of beam motion and beam-target physics.
- Beam-target interaction can double the time-integrated spot size.

Case	Cathode dV_K kV	Anode dV_A kV	Energy KE MeV	Current I_b kA	Normalized Emittance en (4-rms) cm-radian	Envelope Radius R@FF cm	dg/g=1.5% Spot-Size dLANL mm	dg/g=0 Spot-Size dLANL mm	XTR Spot-Size dLANL mm
(CE)	0	0	2.000	1.4452	0.0205	0.9781	0.596	0.224	0.260
(WS)	0	0	2.000	1.4710					
1	-25	0	1.975	1.4366	0.02533	0.9378	0.604	0.288	0.341
2	0	-25	1.975	1.4545					
3	-25	-25	1.950	1.4203	0.04503	1.0075	0.741	0.474	0.521
4	-50	0	1.950	1.4025					
5	0	-50	1.950	1.4382					
6	-50	-50	1.900	1.3701	0.11944	1.391	1.207	0.915	0.995
7	-350	0	1.650	1.0093					
8	0	-350	1.650	1.2448	0.4958	2.699	2.587	2.091	2.453

Rule of thumb: add 0.17 mm for every 25 kV fault

In conclusion, Scorpius is reasonably robust to pulsed-power faults occurring in the injector.

- Fault modes were investigated for the nominal tune of the injector anode transport, LIA, and optimized DST/FF.
- It was assumed that the faults occurred during a shot, so no retune possible.
- Two types of faults were considered:
  - Failure of SSPP unit => -25 kV/fault
  - Failure of cell gap/insulator = -50 kV/fault
- TRAK (ray-trace), XTR (envelope), and LSP (PIC) codes were used to simulate the beam from cathode to target (C2T).
- Spot size calculations did not include beam-target interactions.
  - Beam-target physics might double the time-integrated spot due ion defocusing.
- Results were mostly dependent on the net AK voltage.
  - No significant difference in results for anode vs cathode faults

- Rough rule of thumb: the d_{LANL} spot size enlarges by about 0.17 mm for every 25 kV loss of AK voltage.

Thanks for your attention!